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Effective Breast Cancer Vaccine Development

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13. ABSTRACT (Maximum 200 Words) T cell tolerance to tumor-associated antigens is a significant barrier to immune based treatments of human cancers. One such tumor-associated antigen is the proto-oncogene <i>HER-2/neu (neu)</i> which is overexpressed in 35-40% of all human breast cancers. Although patients with neu expressing tumors develop antibody and T cell responses to this antigen, these responses are weak and unable to hinder tumor growth. Our work has focused on understanding these mechanisms of T cell tolerance using the <i>neu-N</i> transgenic mice that express the wild type rat <i>neu</i> cDNA under control of the MMTV promoter. Since neu is an endogenously expressed antigen, profound neu-specific immune tolerance exists in the <i>neu-N</i> mice. We previously reported the immunodominant T cell epitope of neu recognized by parental FVB/N mice, RNEU ₄₂₀₋₄₂₉ . We have investigated whether altering RNEU ₄₂₀₋₄₂₉ can generate a more immunogenic peptide that will result in better protection from a HER-2/neu expressing tumor in the <i>neu-N</i> mice. Also, using GFP-expressing RNEU ₄₂₀₋₄₂₉ -specific T cells, we demonstrate that high avidity CTL cannot persist in the periphery of <i>neu-N</i> mice but do persist in the periphery of parental mice. Further studies are underway to understand the role other immune cells (such as CD4 ⁺ CD25 ⁺ regulatory T cells) play in CD8 ⁺ T cell tolerance. This work to further understand the mechanisms of T cell tolerance in this cancer model should lead to even further improvements in vaccination strategy for cancer immunotherapies.				
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Introduction

In humans, the proto-oncogene *HER-2/neu* (*neu*) is overexpressed in 35-40% of all breast cancers (1). Although patients with *neu* expressing tumors develop antibody and T cell responses to this antigen, these responses are weak and unable to hinder tumor growth. This suggests that T cell tolerance is a significant barrier to immune based treatments that target *neu* and most likely other antigens expressed by breast cancers. *neu*-N transgenic mice express the wild type rat *neu* cDNA under control of the MMTV promoter (2). Female mice spontaneously develop focal mammary tumors which overexpress the transgene in a stochastic manner starting approximately at 4 months of age. Since *neu* is an endogenously expressed antigen, it is likely that *neu*-specific immune tolerance exists in the *neu*-N mice. Three findings strongly support the existence of *neu*-specific tolerance in these mice (3). First, subcutaneous injection of 100-fold less transplantable *neu*-expressing mammary tumors is required for tumor growth in the *neu*-N mice when compared with the parental FVB/N mice. Second, *neu*-specific vaccines designed to prevent tumor development provide long-term prevention of *neu*-expressing tumors in the FVB/N mice but only delay slightly tumor growth in the *neu*-N mice. Third, *neu*-specific CD8⁺ T cells (CTL) derived from FVB/N mice can lyse *neu*-expressing mammary tumors much more effectively than T cells derived from *neu*-N mice. Based on these findings, the *neu*-N transgenic mouse model of mammary tumors provides a clinically relevant model for developing vaccines that overcome tumor tolerance. The overall aim of this work is to determine the mechanism(s) by which immune tolerance of CTL inhibits effective immunization in the *neu*-N transgenic mice.

Body

An amino acid substitution in neu peptide epitope generates more immunogenic peptide

We previously reported the identification of RNEU₄₂₀₋₄₂₉ (PDSLRLDSVF) as the immunodominant epitope in rat *neu* restricted to the MHC class I molecule H-2D^q. This data was used to generate a MHC/peptide tetramer, and this reagent was used to compare the avidities of T cells derived from *neu*-vaccinated FVB/N mice to those from *neu*-N mice. We discovered that T cells from *neu*-N mice were low avidity as compared with T cells from FVB/N mice, which explains in part the tolerance to *neu* in *neu*-N mice.

To try to overcome this tolerance, we searched for altered peptide analogues of the immunodominant *neu* peptide that had enhanced immunogenicity in our system. Altered forms of RNEU₄₂₀₋₄₂₉ were created by substituting alanine at each of the 10 positions. This type of approach has been successful in identifying heteroclitic T cell peptides in both rodent and human settings (4). In the majority of cases, substitutions did not enhance recognition. However, when alanine was substituted for glutamate at position 2, this peptide (designated RNEU₄₂₀₋₄₂₉A2) demonstrated markedly improved recognition by a FVB/N-derived T cell clone in a lysis assay as compared with wild-type peptide (**figure 1**).

To determine if this heteroclitic peptide can immunize mice against mammary tumor expressing the natural RNEU₄₂₀₋₄₂₉ epitope, both wild-type RNEU₄₂₀₋₄₂₉ and the heteroclitic variant RNEU₄₂₀₋₄₂₉A2 were used to vaccinate mice. Dendritic cells derived from FVB/N mice were pulsed *in vitro* with either of these peptides (or with an irrelevant peptide) and then injected subcutaneously into FVB/N and *neu*-N mice followed by a subcutaneous challenge with the *neu*-

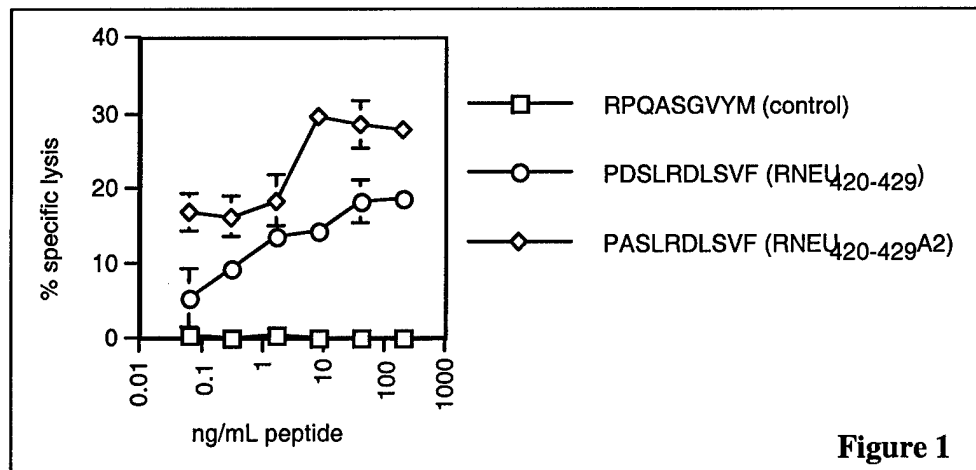


Figure 1

expressing mammary tumor line NT2. As shown in **Figure 2**, mice immunized with dendritic cells pulsed with the wild-type peptide developed tumor at about the same rate as mice immunized

with an irrelevant peptide ($p < 0.15$ for FVB/N mice, $p < 0.39$ for *neu*-N mice). However, FVB/N mice immunized with the heteroclitic peptide showed a lag in tumor growth as compared to FVB/N mice immunized with the irrelevant peptide (**A**, $p < 0.012$). Although not statistically significant, *neu*-N mice demonstrated a promising trend toward protection when vaccinated with the heteroclitic peptide (**B**, $p < 0.21$).

Following the survival of transferred neu-specific T cells in vivo

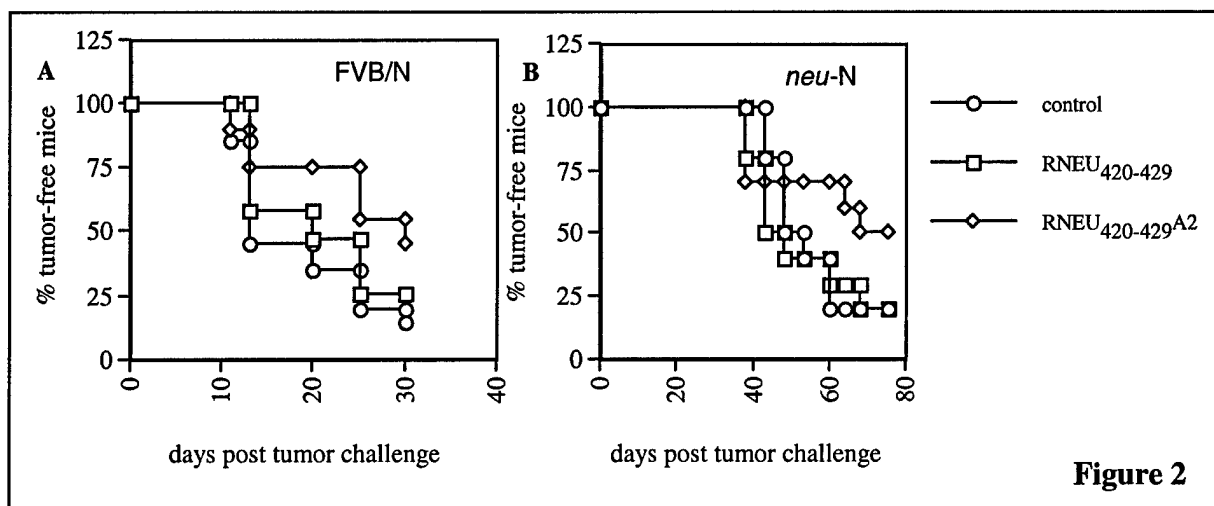


Figure 2

We had shown previously that transfer of a high-avidity RNEU₄₂₀₋₄₂₉-specific parental CTL line into mice given a neu-expressing mammary tumor inoculation provided protection from tumor outgrowth in FVB/N mice but not *neu*-N mice, suggesting that high-avidity neu-specific CTL are deleted or anergized in the periphery of transgenic mice. We had originally proposed to track the fate of neu-specific T cells adoptively transferred into both FVB/N and *neu*-N mice using a MHC/peptide dimer. However, no RNEU₄₂₀₋₄₂₉-specific T cells could be detected in the peripheral organs of mice via flow cytometry staining using either this molecule or the tetramer. The reason for this is not known definitively. Therefore, the fluorescent molecule green fluorescent protein (GFP) was stably transfected via the retrovirus RV-A6.MGIN (5) into the above mentioned CTL lines so that it could be easily detected in the FL1 channel in flow cytometry assays. These GFP-expressing T cells were transferred into FVB/N and *neu*-N mice (**figure 3**). At 3 and 48 hours post T cell transfer, mice were sacrificed and spleens ficolled and washed in FACS buffer prior to FACS analysis. While GFP-positive T cells are detectable in the spleens of both FVB/N and *neu*-N mice at 3 hours (**A** and **B**), after 48 hours they are only detectable in FVB/N mice (**C** and **D**). The inability of high-avidity neu-specific CTL to persist

in the periphery of *neu*-N mice suggests that these CTL are either being actively deleted or else do not receive necessary survival signals in this environment.

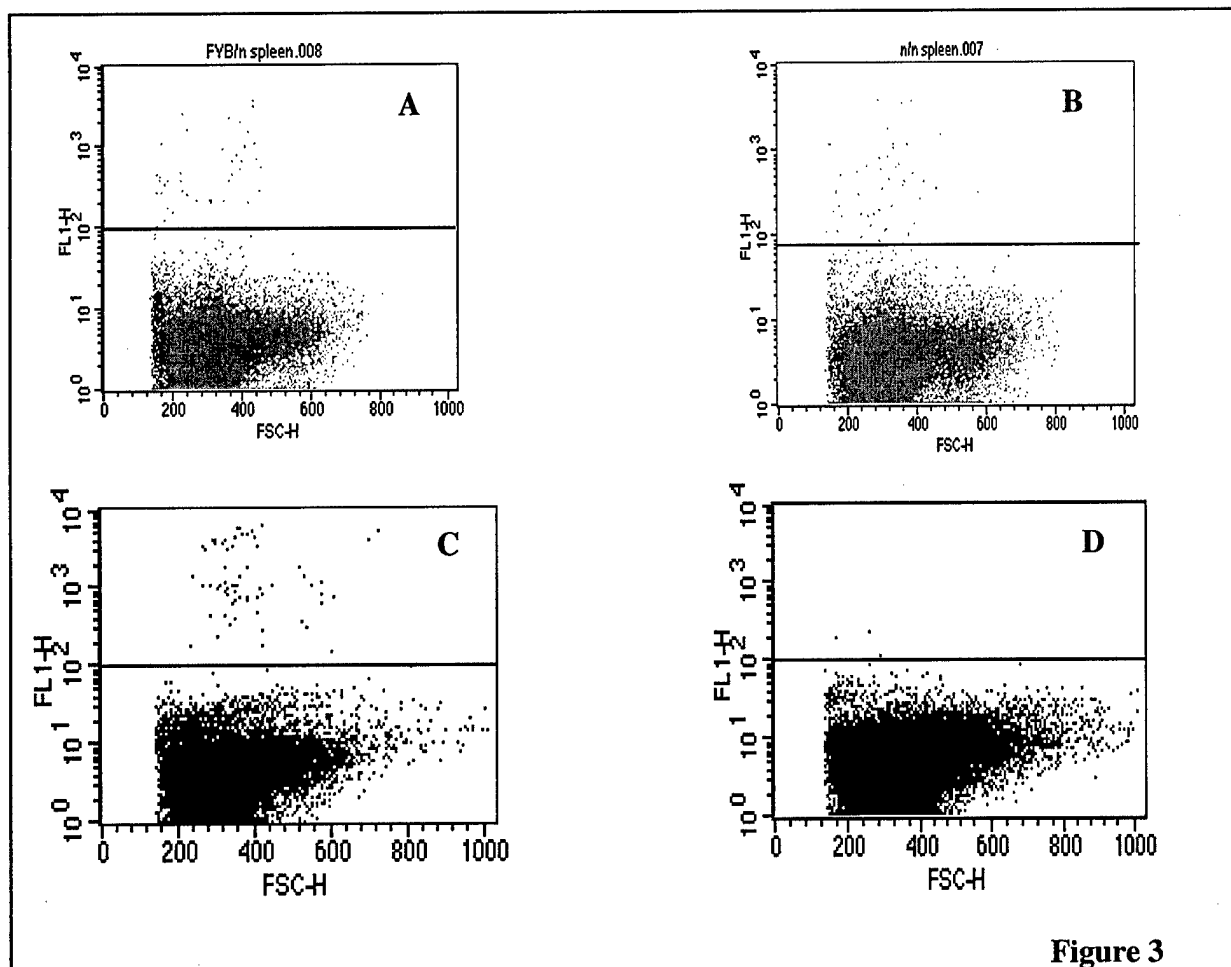


Figure 3

Key Research Accomplishments

- Generated altered, more immunogenic version of previously identified immunodominant MHC Class I epitope in rat neu (RNEU₄₂₀₋₄₂₉→RNEU₄₂₀₋₄₂₉A2).
- Demonstrated that vaccination of both parental and transgenic mice with the altered peptide resulted in improved tumor protection over vaccination with wild-type version.
- Used GFP-expressing RNEU₄₂₀₋₄₂₉-specific T cells to demonstrate that high avidity CTL cannot persist in the periphery of transgenic mice but do persist in the periphery of parental mice.

Reportable Outcomes

- **Ercolini, A.M., Machiels, J.P., Chen, Y.C., Slansky, J.E., Giedlen, M., Reilly, R.T., and Jaffee, E.M.** Identification and Characterization of the Immunodominant Rat HER-2/neu MHC Class I Epitope Presented by Spontaneous Mammary Tumors from HER-2/neu-Transgenic Mice. *The Journal of Immunology*, 2003, 170: 4273-4280.

- **Ercolini, A.M., Ladle, B.H.,** Reilly, R. T., and Jaffee, E. M. Peripheral anergy of high avidity CD8⁺ T cells specific for the immunodominant rat HER-2/neu epitope explains one mechanism of CD8⁺ T cell tolerance. (manuscript in preparation)
- **Ercolini, A.M.,** Armstrong, T., **Ladle, B.H.,** Machiels, J.P., Lei, R.Y., Reilly, R.T. and Jaffee, E.M. An alternate, lower-affinity neu-specific T cell repertoire in HER-2/neu transgenic mice relative to the parental strain may explain neu-specific tolerance to neu-expressing tumors. Keystone Symposia on Basic Aspects of Tumor Immunology, Keystone, CO, Feb. 2003. Abstract #318. Poster Presentation.
- **Ladle, B.H.,** Manning, E.M., Emens, L.A., **Ercolini, A.M.,** Machiels, J.P., Jaffee, E.M. Reversal of CD8⁺ peripheral tolerance in the HER-2/neu transgenic mice by deletion of CD4⁺CD25⁺ regulatory T cells. Keystone Symposia on Basic Aspects of Tumor Immunology, Keystone, CO, Feb. 2003. Abstract #333. Poster Presentation.
- **Ercolini, A.M.,** Armstrong, T.D., **Ladle, B.H.,** Machiels, J.P., Lei, R., Reilly, R.T., and Jaffee, E.M. Presentation at New Investigators' Luncheon entitled "Dissecting the mechanisms of T cell tolerance for more effective breast cancer vaccine development." Department of Defense Breast Cancer Research Program Meeting, Orlando, FL, September 28, 2002. Abstract#P54-12.
- Doctorate of Philosophy Degree in Immunology from The Johns Hopkins University School of Medicine awarded to **Anne M. Ercolini** in February 2003.
- GFP-expressing RNEU₄₂₀₋₄₂₉-specific T cell line
- Post-Doctoral Research Fellow – Position obtained by **Anne M. Ercolini** in March 2003 in the laboratory of Stephen D. Miller, Department of Microbiology-Immunology and Interdepartmental Immunobiology Center, Northwestern University Medical School, 303 E. Chicago Avenue, Chicago, IL 60611

Conclusions

Although the presence of antigen-specific CTL has been demonstrated in patients with tumor, the responses for the most part are weak and unable to hinder the growth of the malignancy. This has been shown in many types of cancer including neu-specific T cells in breast cancer. In some instances this may be due to an ineffective vaccine approach. However, in many cases mechanisms of peripheral T cell tolerance to specific tumor antigens may be at work. A major goal of cancer research is to develop therapies that will reverse the tolerant state and allow T cells to more effectively respond to tumor. *neu*-N transgenic mice display tolerance to the endogenous *neu* transgene and are therefore a clinically relevant model of breast cancer. The aim of this proposal is to dissect the mechanisms of CD8⁺ T cell tolerance in this mouse model. Knowledge of the mechanisms of tolerance in these mice will lead to the development of more effective vaccine strategies that can overcome tolerance to the neu antigen.

We previously identified RNEU₄₂₀₋₄₂₉ as the immunodominant epitope in rat neu, and that vaccinated *neu*-N mice develop low-avidity CTL specific for this peptide as compared with CTL from FVB/N mice. One major goal is to develop vaccine strategies that will allow transgenic mice to develop high-avidity neu-specific T cells. For some antigens, altering the wild-type MHC I epitope so that it binds more strongly to MHC and/or demonstrates greater recognition *in vitro* by antigen specific T cells improves the immunization potential and the clinical outcome (6). Here, we show that vaccinating FVB/N and *neu*-N mice with dendritic cells pulsed with a heteroclitic variant of the wild-type epitope also induces improved protection against tumors that express the natural RNEU₄₂₀₋₄₂₉ epitope as compared with immunization with the RNEU₄₂₀₋₄₂₉ epitope itself. Further study needs to be done to determine if improvement in tumor-free survival

is due to the generation of higher-avidity CTL in *neu*-N mice vaccinated with the heteroclitic peptide. Although this regimen is so far less efficacious than the vaccination strategies we have developed using the entire neu protein, it is hoped that further study will build upon the principles gleaned from these experiments and lead to improvements relevant to treatment strategies in patients.

We showed previously that high avidity RNEU₄₂₀₋₄₂₉ specific T cells derived from parental mice could cure parental mice of transplanted neu-expressing tumor but could not cure transgenic mice. We hypothesized that this was due to the anergy or deletion of high avidity T cells in *neu*-N mice and wanted to track their fate in the periphery of mice after transfer. Using a GFP-expressing CTL line derived from FVB/N mice, we showed that high avidity RNEU₄₂₀₋₄₂₉-specific T cells persist in the periphery of FVB/N mice but not *neu*-N mice.

Further studies are underway to understand the role other immune cells play in this CD8⁺ T cell tolerance. Initial experiments indicate that CD4⁺CD25⁺ regulatory T cells from *neu*-N mice are able to suppress RNEU₄₂₀₋₄₂₉ specific T cells from FVB/N mice. Other initial experiments show that depletion of CD4⁺CD25⁺ regulatory T cells in *neu*-N mice using the monoclonal antibody PC61 (rat IgG specific to mouse CD25) increases the number of RNEU₄₂₀₋₄₂₉ specific T cells that can be detected following a HER-2/neu targeted vaccine.

In summary, it is likely that further investigation of the mechanism of T cell tolerance in this cancer model will lead to even further improvements in vaccination strategy for the eradication of tumors.

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APPENDIX COVER SHEET

Identification and Characterization of the Immunodominant Rat HER-2/neu MHC Class I Epitope Presented by Spontaneous Mammary Tumors from HER-2/neu-Transgenic Mice¹

Anne M. Ercolini, Jean-Pascal H. Machiels,² Yi Cheng Chen, Jill E. Slansky,³ Martin Giedlen,⁴ R. Todd Reilly, and Elizabeth M. Jaffee⁵

The HER-2/neu (*neu*-N)-transgenic mice are a clinically relevant model of breast cancer. They are derived from the parental FVB/N mouse strain and are transgenic for the rat form of the proto-oncogene HER-2/neu (*neu*). In this study, we report the identification of a MHC class I peptide in the *neu* protein that is recognized by CD8⁺ T cells derived from vaccinated FVB/N mice. This 10-mer was recognized by all tumor-specific FVB/N T cells generated regardless of the TCR V β region expressed by the T cell or the method of vaccination used, establishing it as the immunodominant MHC class I epitope in *neu*. T cells specific for this epitope were able to cure FVB/N mice of transplanted *neu*-expressing tumor cells, demonstrating that this is a naturally processed peptide. Altered peptide analogs of the epitope were analyzed for immunogenicity. Vaccination with dendritic cells pulsed with a heteroclitic peptide provided FVB/N and *neu*-N mice with increased protection against tumor challenge as compared with mice immunized with dendritic cells loaded with either wild-type or irrelevant peptide. Discovery of this epitope allows for better characterization of the CD8⁺ T cell responses in the *neu*-N mouse model in which *neu*-specific tolerance must be overcome to produce effective antitumor immunity. *The Journal of Immunology*, 2003, 170: 4273–4280.

An important role for Ag-specific CD8⁺ CTLs in antitumor immunity has been demonstrated in both murine tumor models and cancer patients. In mice, immunization with model and naturally expressed tumor Ags or their MHC class I (MHC-I)⁶ epitopes induces antitumor CTL that mediate in vivo tumor rejection (1–12). Patients with established disease have shown some response when given adoptively transferred tumor-specific CTL (13–15). Similarly, clinical trials testing the efficacy of immunizing with MHC-I tumor epitopes from the human pap-

illoma virus Ag E7 have resulted in T cell responses in some patients with cervical cancer (16–18). Several trials undertaken with peptides derived from melanoma-associated Ags have resulted in the induction and expansion of Ag-specific CTL. In some cases, immunization was also associated with clinical responses (19–22). However, in the majority of patients, immunization with MHC-I peptides induces T cell responses that are weak and ineffective in inducing significant tumor regression. As with all cancer therapies, the application of spontaneously arising mouse cancer models is central to the development of enhanced immunotherapies for human cancer (23).

We previously described *neu*-N-transgenic mice as a model of breast cancer that closely mimics immune tolerance described in some patients with cancer (24). These mice, derived from the parental FVB/N strain, express the wild-type rat HER-2/neu (*neu*) cDNA under the control of a mouse mammary tumor virus promoter (25). Female mice spontaneously and stochastically develop mammary tumors beginning at 4 mo of age. Mammary glands that have become tumorigenic overexpress the *neu* transgene relative to *neu* expression in normal glands in the same mice. Because the *neu* tumor Ag is endogenous to the host, this allows for the development of tolerance to the Ag, as evidenced by the poor ability of these mice to develop *neu*-specific antitumor immunity following vaccination as compared with the parental FVB/N mice. In the parental strain, depletion of CD8⁺ T cells before *neu*-specific vaccination inhibits their ability to reject a subsequent tumor challenge (24). Similarly, depletion of CD8⁺ T cells in transgenic mice before vaccination accelerates tumor outgrowth (26–29). However, unlike the parental mice, the transgenic mice are rarely cured of *neu*-expressing tumors. These data suggest that *neu*-specific CTL in *neu*-N mice are either weak lytic agents or are actively tolerized, either through deletion or anergy induction among high-avidity T cells.

The current study was designed to identify epitopes expressed by the rat *neu* and recognized by FVB/N (H-2^d)-derived CTL.

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⁶ Abbreviations used in this paper: MHC-I, MHC class I; HA, hemagglutinin; ICS, intracellular cytokine staining.

Identification and characterization of these epitopes are critical to understanding the difference in neu-reactive T cell responses between the transgenic and parental mice. Numerous tolerance studies have shown that T cells reactive with endogenous Ags expressed in the thymus are deleted (30–33), although some T cells can escape and exist in the periphery in a functionally unresponsive state (30, 34, 35). Similarly, T cells reactive with endogenous Ags not expressed in the thymus may be deleted or rendered non-responsive in the periphery (36–38). Knowledge of the MHC-I epitopes in neu will allow us to study the fate of T cell responses directed at these epitopes in the neu-N-transgenic tolerant mice. In addition, it may be possible to alter these epitopes to identify heteroclitic epitopes with improved immunogenicity in the transgenic mice.

We have identified the immunodominant MHC-I epitope in the rat neu protein. This peptide is recognized by all neu-specific T cell lines and clones we derived from the splenocytes of vaccinated FVB/N mice, regardless of the TCR V β region expressed. In addition, we show that adoptive transfer of T cells specific for this peptide is protective in vivo. Furthermore, immunization with a heteroclitic version of this peptide is also protective against challenge with mammary tumors expressing the naturally processed epitope.

Materials and Methods

Peptides and primers

A panel of 135 peptides from fragment 4 (see Fig. 2) used in the initial screening were synthesized by Chiron (Emeryville, CA). All other peptides (>95% purity) were from the Johns Hopkins Biosynthesis and Sequence Facility (Department of Biochemistry, Johns Hopkins School of Medicine, Baltimore, MD). The PCR primers used to create the neu fragments (see Fig. 1) are as follows: fragment 1 (bp 1–508), 5'-CCGGGCCGAATTCGCAATGATC and 3'-CCCCGAATTCCTACTGAGGGTCCCCACGGA TCAA; fragment 2 (bp 458–886), 5'-GACATGAAGTTGCGGCTCC CTAGTCTCACAGAGACTCTGAAG and 3'-CCCCGAATTCCTACTC AGGGTTGTGTCATGGACTC; fragment 3 (bp 836–1294), 5'-GACATGA AGTTGCGGCTCCCTGCCCTCGTCACCTACAACACA and 3'-CCCC GAATTCCTAGAGGTACCGGAGACTGTCTGG; fragment 4 (bp 1244–1675), 5'-GACATGAAGTTGCGGCTCCCTATCACAGGTACCTGTGTA CATC and 3'-CCCCGAATTCCTACTTCCATACCTCGGCTACCTCTC; fragment 5 (bp 1607–2077), 5'-GACATGAAGTTGCGGCTCCCTAC CAGTGTGTCAACTGCAGT and 3'-CCCCGGTACCCTAGATCTTC TGCTCTCTCTGTTT; fragment 6 (bp 2009–2476), 5'-GACATGAAGT TGGGCTCCCTGGCGTCTGCTGCTCTGATC and 3'-CCCCGGTA CCCTAACCTCGGTGTTCTCGGACATG; fragment 7 (bp 2405–2872), 5'-GACATGAAGTTGCGGCTCCCTTCCACAGTACAGCTGGTGACA and 3'-CCCCGGTACCCTAGCAGATTGGAGGCTGAGGTGAG; fragment 8 (bp 2801–3271), 5'-GACATGAAGTTGCGGCTCCCTGATGG AATCCAGCCCGGGAG and 3'-CCCCGGTACCCTACCCTTCC GAGGGAGCCAGTGG; and fragment 9 (bp 3203–3796), 5'-GACATGAAGTTGCGGCTCCCTGAGCTGACACTGGGCTGGAG and 3'-CCCCGGTACCCTATACAGGTACATCCAGGCTCAG. Each fragment was ligated into the pcDNA3.1 mammalian transfection vector (Invitrogen, Carlsbad, CA) at the multicloning site.

Cell lines and medium

The IT22 cell line derives from a spontaneously transformed mouse fibroblast line as described previously (39). NIH 3T3 cells are a mouse fibroblast line (ATCC CRL-1658; American Type Culture Collection (ATCC), Manassas, VA). Rat neu cDNA was cloned from pSV2-neu-N (40) and ligated into the pcDNA3.1 vector (Invitrogen). IT22 cells were transfected with this construct by electroporation ($20 \mu\text{g}/10^7$ cells) to produce IT22neu cells. The human B7-1 gene was retrovirally inserted into rat neu-expressing NIH 3T3 cells (3T3neu; ATCC CRL-1915) using previously described methods (41) to produce 3T3neuB7-1 cells. The same neu-expressing NIH 3T3 cells were transduced with a murine GM-CSF retrovirus using the same methods for inserting the B7-1 gene to create 3T3neuGM vaccine cells. L-D a cells and L-L q cells are murine fibroblast cell lines transfected with murine H-2D a or -L q , respectively (42). All of the above cell lines were maintained at 37°C and 10% CO $_2$ in DMEM (Life Technologies, Rockville, MD) supplemented with 10% bovine calf serum (HyClone, Logan, UT), 1% L-glutamine (JRH Biosciences, Lenexa, KS), 1% nonessential amino acids (Sigma-Aldrich, St. Louis, MO), 1% sodium pyruvate (Sigma-Aldrich), and 0.5% penicillin/streptomycin (Sigma-Aldrich). The NT2 and

NT5B7-1 neu-expressing tumor lines are derived from spontaneous mammary tumors excised from the neu-N mice as previously described (24, 43).

Cloning and transfection of H-2D a

Murine H-2D a was cloned from the L-D a cell line (5' primer, ATGGCTC CGCGCACGCTGCT; 3' primer, TCACGCTTTACAATCTCGGA) and ligated into pcDNA3.1. The T2 cell line is a B lymphoblast/T lymphoblast hybrid human cell line deficient in the MHC-I TAP transporter molecule (ATCC CRL-1992). These cells were transfected with D a by electroporation ($20 \mu\text{g}/1 \times 10^7$ cells) to create the T2D a cell line. T2D a cells were maintained at 37°C and 5% CO $_2$ in RPMI 1640 (Life Technologies) supplemented with 10% FBS (HyClone), 1% L-glutamine, 1% nonessential amino acids, 1% sodium pyruvate, and 0.5% penicillin/streptomycin.

neu-specific T cell lines and clones and hemagglutinin (HA)-specific T cell line

Some CD8 $^+$ T cell lines were derived from FVB/N mice that were s.c. vaccinated with 1×10^6 irradiated 3T3neuGM cells at each of three sites (two forelimbs and one hindlimb). Mice were sacrificed, and spleens were excised 2 wk later. Splenocyte cultures were initially stimulated every 5 days with irradiated, IFN- γ -treated NT5B7-1 cells and then every 9 days by the addition of irradiated 3T3neuB7-1 cells as stimulators and FVB/N-derived splenocytes as feeders. Clones were developed from this line by limiting dilution. Other CD8 $^+$ T cell lines were produced from the splenocytes of mice vaccinated with a neu-expressing recombinant vaccinia or neu plasmid DNA as described previously (24). A T cell line specific for the irrelevant Ag HA was derived from mice vaccinated with HA recombinant vaccinia virus as described previously (44). T cells were maintained at 37°C and 5% CO $_2$ in CTL medium (RPMI 1640 supplemented with 10% FBS, 1% L-glutamine, 0.1% 2-ME (Sigma-Aldrich), and 0.5% penicillin/streptomycin) supplemented with 10 cetus U/ml murine IL-2 (supernatant from B16 IL-2 line (45)).

Chromium release assays

Lysis assays were performed in triplicate in 96-well V-bottom plates as previously described (24). Briefly, target cells were resuspended in 100 μl of CTL medium and labeled with 0.2 mCi of $^{51}\text{Cr}/2 \times 10^6$ cells at 37°C and 5% CO $_2$ for 1 h. Cells were washed in CTL medium and resuspended at 6×10^4 cells/ml in RPMI 1640. To pulse peptide onto targets, 100 μl of peptide in RPMI 1640 was added to 50- μl targets for 1 h at room temperature in each well. After the removal of 100 μl of supernatant, 150 μl of T cells in CTL medium was added for the indicated E:T ratio. After a 4-h incubation, 100 μl of supernatant was assayed for ^{51}Cr release and percent specific lysis was determined by the formula: (^{51}Cr release sample – spontaneous ^{51}Cr release target alone)/(maximum ^{51}Cr release target alone – spontaneous ^{51}Cr release target alone) \times 100. For the Ab blocking assays, the H-2D a Ab 30-5-7S (ATCC HB-31) was added for 30 min at 37°C to 100 μl of target cells resuspended in CTL medium at a final concentration of 50 μM before addition of effector T cells.

Development and transfection of neu fragments

Nine overlapping fragments of the neu cDNA were created using specific primers and PCR amplification (Fig. 1A) and then ligated into pcDNA3.1. The fragment constructs were then transfected into NIH 3T3 cells using electroporation ($20 \mu\text{g}/1 \times 10^7$ cells) or Lipofectamine ($1.5 \mu\text{g}/3 \times 10^5$ cells; Life Technologies). Limiting dilution produced several clones of each fragment. RT-PCR was performed using primers described above to determine which clones expressed fragment mRNA.

Mice and dendritic cell immunizations

FVB/N mice were purchased at 6–8 wk of age from the National Cancer Institute (Bethesda, MD). neu-N mice (25) were bred to homozygosity as verified by Southern blot analysis. Splenic dendritic cells were generated from FVB/N mice as previously described (46). On the day of immunization, cells were collected, resuspended at 4×10^6 /ml in AIM-V medium (Life Technologies), and pulsed with 300 $\mu\text{g}/\text{ml}$ peptide for 3 h. Cells were then washed three times in HBSS (pH 7.4) and resuspended at 2×10^6 cells/ml. Mice were given 0.1 ml s.c. injections in each hindlimb on days 0 and 7 and challenged with NT2 mammary tumor cells in the right hindlimb on day 14.

GM-CSF release ELISA

Peptides were pulsed onto NIH 3T3 cells (which were grown overnight at 26°C to increase the number of empty MHC on the cell surface) in RPMI 1640 at 26°C for 1 h at a final concentration of 0.1 μM . Targets were then

washed twice in CTL medium, and 1×10^5 T cells were added for a 1:1 E:T ratio. Plates were incubated at 37°C and 5% CO₂ for 24 h, and supernatants were harvested for the ELISA (Endogen, Woburn, MA). For the screening of *neu* fragments, 1×10^5 T cells and 3×10^5 targets were plated in CTL medium for 24 h and an ELISA was performed.

Flow cytometry (FACS)

Cells were stained by washing them two times in FACS buffer (1× HBSS (pH 7.4), 2% FBS, 1% HEPES (Life Technologies), and 0.1% NaN₃ (Sigma-Aldrich)) and incubating with Ab for 20 min at 4°C. Staining of TCR Vβ4, Vβ14, and Vβ17 was done using supernatants from hybridomas KT4-10, 14-2, and KJ23, respectively (47). Abs to Vβ2, -6, and -7, and fluorescence-conjugated secondary Abs were purchased from BD Pharmingen (La Jolla, CA). Ab to CD8 was purified from the 2.43 hybridoma (ATCC HB-27). MHC staining was done using supernatant collected from hybridomas 30-5-7S, 113, and 28-14-8S, which are specific for H-2D^a (42). The secondary Ab for all three Abs was FITC-conjugated goat anti-mouse IgG (BD Pharmingen).

Intracellular cytokine staining (ICS)

ICS was performed as directed using a BD Pharmingen kit for detection of murine IFN-γ. Briefly, 1×10^6 splenocytes (nylon wool purified to deplete B cells and macrophages) were incubated 12–16 h with an equal ratio of indicated targets in the presence of GolgiStop. Cells were washed in FACS buffer and stained with FITC-conjugated Ab to CD8, fixed and permeabilized, and stained with PE-conjugated Ab to IFN-γ.

Results

Generation of *neu*-specific CD8⁺ T cells from vaccinated FVB/N mice

Three T cell lines were generated to characterize the T cell populations that result from different vaccination experiments as well as from different *neu* targeted vaccine approaches shown to be potent in other tumor models (48). A T cell line was therefore generated from mice vaccinated with the 3T3neuGM whole cell vaccine, and 11 *neu*-specific T cell clones were derived from this line. In addition, lines were created from mice vaccinated with the vaccinia vector expressing the entire *neu* protein and from mice vaccinated with *neu* plasmid DNA. All lines and clones were shown to lyse the full-length *neu* protein in a ⁵¹Cr release assay using 3T3neu vs 3T3 wild-type targets (not shown). Analysis of the Vβ usage of these T cell lines and clones suggests that the *neu* CD8⁺ T cell response is oligoclonal. Specifically, TCRs utilizing six Vβ regions (TCR Vβ2, -4, -6, -7, -14, and -17) were identified (data not shown).

Identification of RNEU_{420–429}, a peptide epitope contained in the extracellular domain of the rat *neu* protein, as the T cell target of all FVB/N-derived T cell lines and clones

As an initial approach to roughly map the position of *neu* epitopes, the *neu* cDNA was divided into nine approximately equal fragments overlapping by 15–25 aa (Fig. 1A). NIH 3T3 cells were

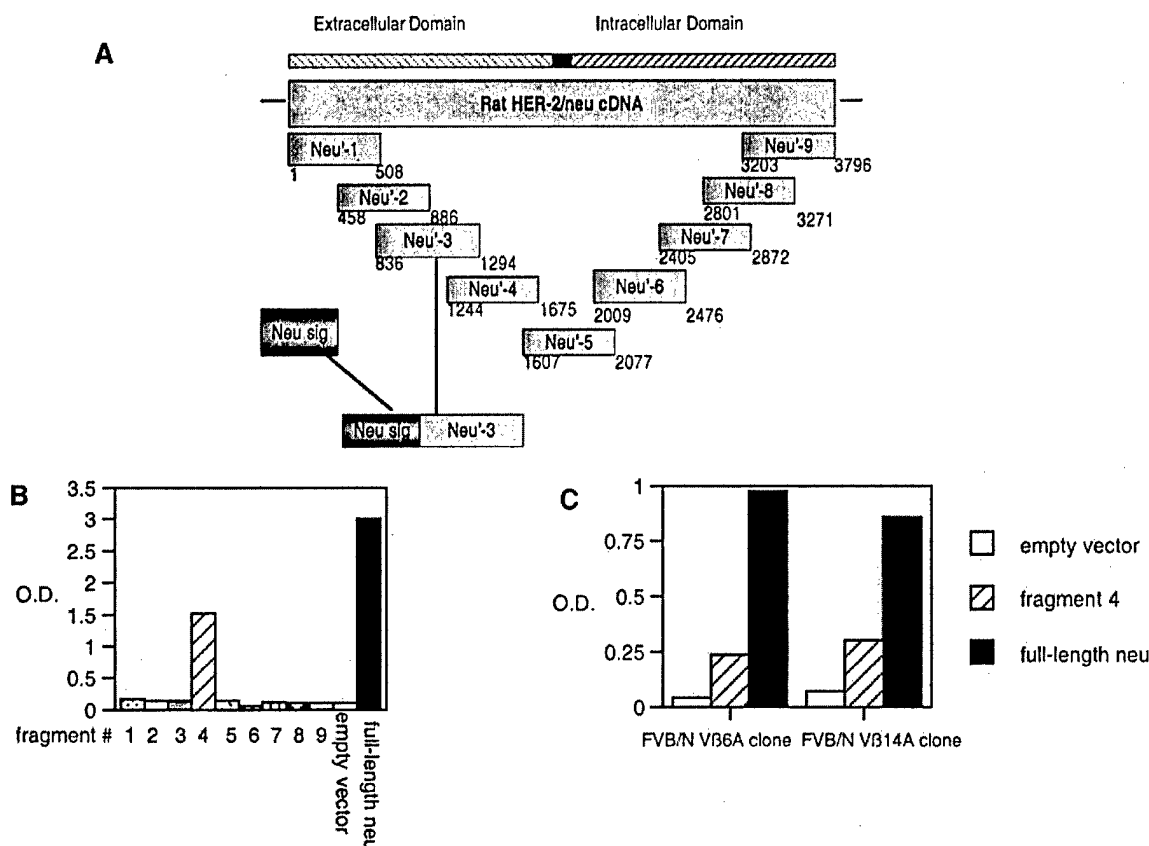


FIGURE 1. Extracellular fragment 4 of *neu* contains a *neu* MHC-I epitope recognized by the FVB/N-derived T cell clones. **A**, Nine overlapping fragments of *neu* cDNA were created using specific primers and PCR amplification. The numbers under each fragment refer to the starting and ending base pair within the entire *neu* cDNA. Each fragment was sequenced and confirmed to be the original rat *neu* sequence before ligation into the vector pcDNA3.1. The fragments were then transfected into 3T3 cells for use as targets in T cell assays. T cells (1×10^5) and 3×10^5 targets were plated in duplicate in 96-well plates and incubated at 37°C for 24 h. Supernatants were collected and tested for levels of GM-CSF by ELISA. Data are shown as degree of color change (OD). Effectors were FVB/N Vβ4A clone (TCR Vβ4) (**B**) and FVB/N Vβ6A clone (TCR Vβ6) and FVB/N Vβ14A clone (TCR Vβ14) (**C**). T cells show recognition of full-length *neu* (■) and of fragment 4 (▨).

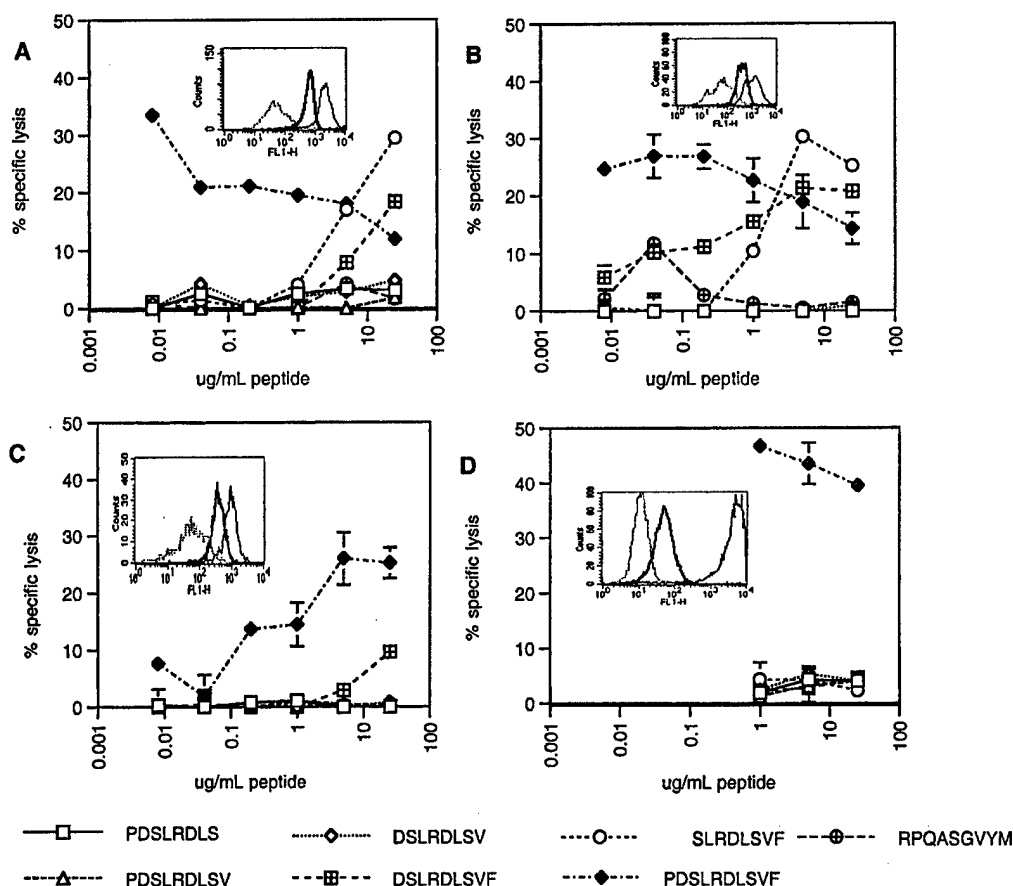


FIGURE 2. The original identified 10-mer RNEU₄₂₀₋₄₂₉ is the optimal epitope recognized by neu-specific T cell clones. Full-length and truncated versions of the epitope (as well as the irrelevant lymphocytic choriomeningitis virus nucleoprotein peptide NP₁₁₈₋₁₂₆ (68)) were pulsed onto 3×10^5 chromium-labeled IT22 cells for 1 h at 37°C. T cells were added before a 4-h incubation at 37°C. E:T ratios ranged from 15:1 to 25:1. Effectors were FVB/N Vβ2A clone (Vβ2) (A), FVB/N Vβ4A clone (Vβ4) (B), FVB/N Vβ6A clone (Vβ6) (C), and FVB/N Vβ14A clone (Vβ14) (D). Insets, Surface staining of T cell clones. Effectors were stained with Ab to CD8 (thin line), Ab to appropriate TCR Vβ region (thick line), or the irrelevant Ab rat IgG (dotted line).

transfected with these constructs and used as targets in GM-CSF release assays to identify which fragment contained the peptide(s) recognized by the clones. Fig. 1B shows recognition of 3T3 cells expressing fragment 4 (aa 410–553) by the FVB/N-derived T cell clone FVB/N Vβ4A (expressing TCR Vβ4). Recognition of fragment 4 was also seen with FVB/N Vβ6A clone (TCR Vβ6) and FVB/N Vβ14A clone (TCR Vβ14) (Fig. 1C). This fragment is located in the extracellular domain of neu near the transmembrane region.

Peptides 10 aa in length were synthesized, and these peptides spanned the entire sequence of fragment 4 (excluding the overlapping regions with fragments 3 and 5) and overlapped by nine residues each. Of the 135 peptides made, one (RNEU₄₂₀₋₄₂₉) was consistently recognized by clones in GM-CSF release ELISA (data not shown). This peptide (PDSLRDLSVF), along with its 8- and 9-aa derivatives, was synthesized and tested for recognition by neu-specific T cells in Cr⁵¹ release lysis assays. As shown in Fig. 2, the 10-mer was recognized more efficiently than the shorter peptides regardless of the TCR Vβ region expressed by the T cell. This peptide was subsequently found to be recognized by all T cell lines and clones derived, suggesting that RNEU₄₂₀₋₄₂₉ is the immunodominant MHC-I neu epitope recognized by FVB/N-derived T cells. To further analyze the CD8⁺ T cell response to neu in FVB/N mice, frequency analysis was performed on the spleens of five individual mice given a s.c. 3T3neuGM vaccine. Fourteen days after vaccination, spleens were excised and cultured with 3T3neuB7-1 cells for 7 days before performing ICS to determine the response to full-length neu and to RNEU₄₂₀₋₄₂₉. As shown in

Table I, all vaccinated FVB/N mice developed CD8⁺ T cells that were specific for both full-length neu and for RNEU₄₂₀₋₄₂₉. This further supports the immunodominance of RNEU₄₂₀₋₄₂₉ in

Table I. T cell specificity of vaccinated FVB/N and neu-N mice^a

Mouse No.	% neu Specific ^b	% RNEU ₄₂₀₋₄₂₉ Specific ^c
FVB/N 1	1.83	2.48
FVB/N 2	0.88	1.92
FVB/N 3	1.47	2.75
FVB/N 4	0.06	0.48
FVB/N 5	0.28	1.16
neu-N 1	0.00	0.32
neu-N 2	0.13	0.22
neu-N 3	0.00	0.23
neu-N 4	0.00	0.00
neu-N 5	0.02	0.26
neu-N 6	0.00	0.07
neu-N 7	0.00	0.06
neu-N 8	0.16	0.00
neu-N 9	0.00	0.04
neu-N 10	0.14	0.00

^a Specificity determined by the percentage of CD8⁺ splenocytes staining positive for IFN-γ in response to target in ICS assay.

^b neu specificity determined by the percentage responding to IT22neu minus the percentage responding to IT22.

^c RNEU₄₂₀₋₄₂₉ specificity determined by the percentage responding to T2D^a cells pulsed with RNEU₄₂₀₋₄₂₉ minus the percentage responding to T2D^a cells pulsed with the irrelevant peptide NP₁₁₈₋₁₂₆.

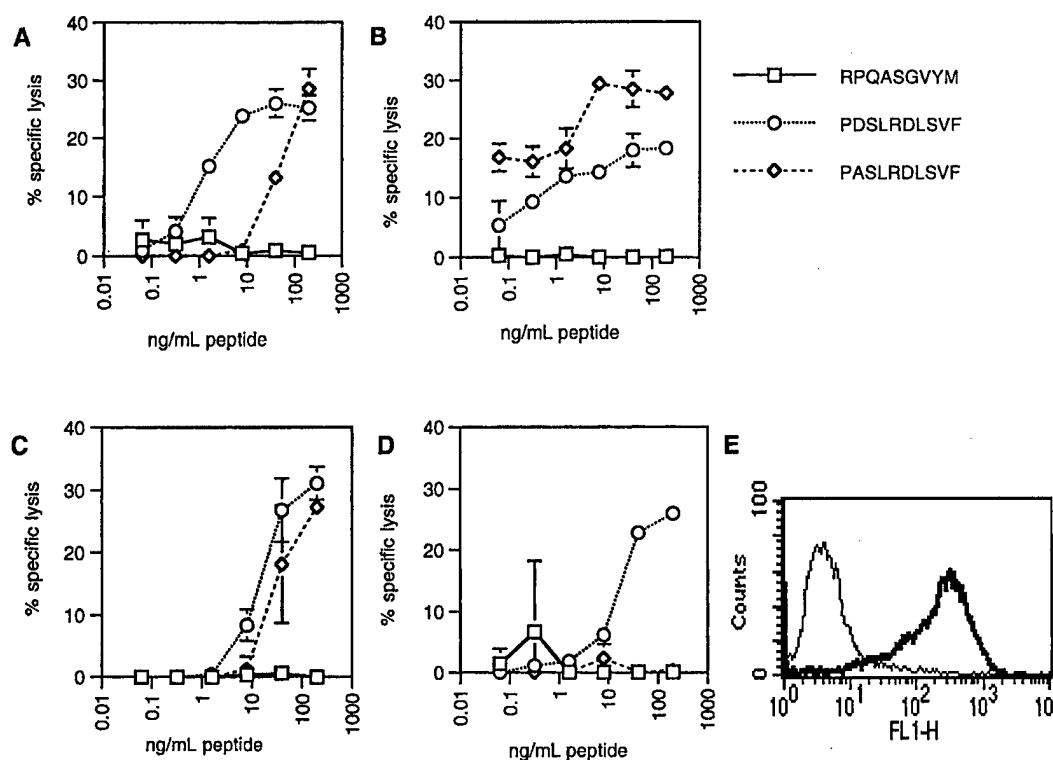


FIGURE 3. H-2D^q is the restricting MHC molecule for the recognition of RNEU₄₂₀₋₄₂₉ by FVB/N T cell clones. T2 cells were transfected via electroporation (20 μ g/10⁷ cells) with D^q cDNA to create T2D^q cells. Chromium-labeled T2D^q cells (3 \times 10³) were pulsed for 1 h with either RNEU₄₂₀₋₄₂₉ or the heteroclitic variant RNEU₄₂₀₋₄₂₉A2. T cells (3 \times 10⁴) were then incubated with the targets for 4 h at 37°C. Effectors were FVB/N Vβ2A clone (Vβ2) (A), FVB/N Vβ4A clone (Vβ4) (B), FVB/N Vβ6A clone (Vβ6) (C), and FVB/N Vβ14A clone (Vβ14) (D). T cell clone FVB/N Vβ4A demonstrates enhanced lysis of the RNEU₄₂₀₋₄₂₉ peptide with an alanine substituted at position 2 (RNEU₄₂₀₋₄₂₉A2). E, T2D^q cells were incubated with Ab to D^q (28-14-8S) followed by FITC-conjugated Ab to mouse IgG (thick line) to confirm surface expression of the MHC molecule (thin line, secondary Ab alone).

FVB/N mice. The same analysis was done on the spleens of 10 individual *neu*-N mice given the same vaccine. As shown in Table I, the tolerized *neu*-N mice do not demonstrate appreciable T cell activity for the immunodominant epitope.

H-2D^q is the restriction element for RNEU₄₂₀₋₄₂₉

Initial CTL blocking studies using an Ab specific for H-2D^q and -L^q (30-5-7S) indicated that lysis of *neu* was restricted to one of these two molecules. MHC restriction was further determined by pulsing RNEU₄₂₀₋₄₂₉ onto mouse L cells that were transfected with either H-2D^q or -L^q. FVB/N Vβ4A clone cells lysed targets transfected with D^q but not those transfected with L^q (data not shown). The D^q molecule was then cloned and transfected into T2 cells. When pulsed with RNEU₄₂₀₋₄₂₉, T2D^q cells were recognized in a ⁵¹Cr release assay by all FVB/N-derived T cell lines and clones. Lysis of T2D^q cells pulsed with decreasing concentrations of the RNEU₄₂₀₋₄₂₉ peptide is shown in Fig. 3 for the four T cell clones also evaluated in Fig. 2. These data established D^q as the restricting MHC-I molecule for RNEU₄₂₀₋₄₂₉.

Adoptive transfer of RNEU₄₂₀₋₄₂₉-specific T cells into tumor-bearing FVB/N mice confirms that this peptide is a tumor rejection epitope naturally expressed by mammary tumor cells *in vivo*

FVB/N mice were given a s.c. leg injection of *neu*-expressing tumor cells (NT2) followed 1 day later by i.v. transfer of an FVB/N T cell line (derived from mice given *neu* plasmid vaccine) specific for RNEU₄₂₀₋₄₂₉. This line was chosen because it demonstrated the highest lysis of NT2 cells *in vitro*. As shown in Fig. 4, mice receiving these T cells showed protection from tumor outgrowth as

compared with mice receiving a control T cell line specific for the irrelevant Ag HA ($p < 0.0008$). This experiment was repeated using several RNEU₄₂₀₋₄₂₉ specific T cell clones and lines with similar results.

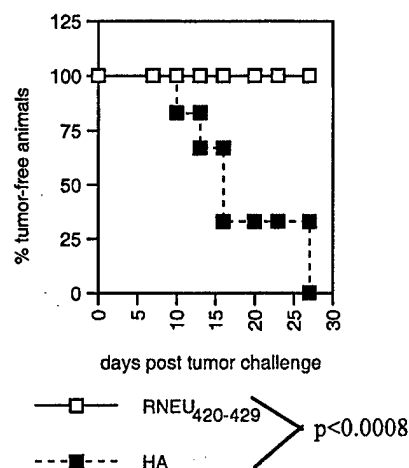


FIGURE 4. Confirmation that RNEU₄₂₀₋₄₂₉ is the naturally processed mammary tumor epitope expressed *in vivo*. FVB/N mice (9–10 mice/group) were given a s.c. leg injection of 5×10^6 *neu*-expressing tumor cells (NT2 cells derived from spontaneously arising mammary tumors in *neu*-N mice). One day later, mice were given an i.v. transfer of 1×10^7 CD8⁺ T cells specific for either RNEU₄₂₀₋₄₂₉ or for the irrelevant Ag HA. Mice were observed twice a week for the development of tumor in the leg. Additional independent studies were performed with other T cell clones and lines with similar results.

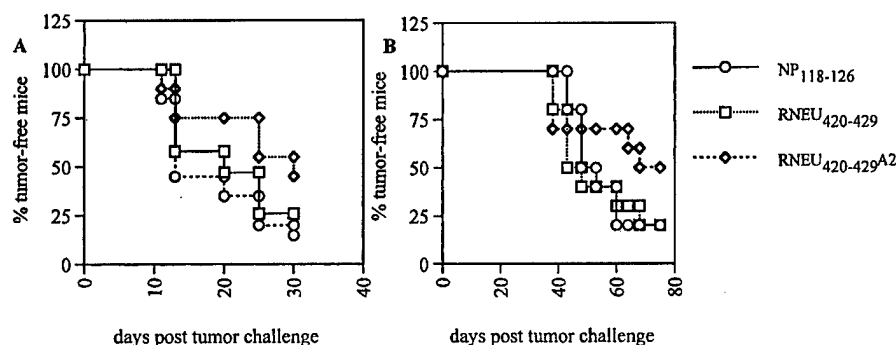


FIGURE 5. Mice immunized with the alanine substituted variant of RNEU₄₂₀₋₄₂₉ show a lag in neu-expressing tumor growth as compared with immunization with wild-type RNEU₄₂₀₋₄₂₉ or the irrelevant peptide. Splenic dendritic cells generated from FVB/N mice were pulsed with 300 μ g/ml either RNEU₄₂₀₋₄₂₉, RNEU₄₂₀₋₄₂₉A2, or the lymphocytic choriomeningitis virus NP₁₁₈₋₁₂₆ peptide. Subcutaneous injections (0.1 ml) of 2×10^5 cells were given in each hindlimb on days 0 and 7. Mice were challenged s.c. with NT2 tumor cells on day 14. A, FVB/N mice (19–20/group) were given 5×10^6 NT2 cells. B, neu-N mice (10/group) were given 5×10^4 NT2 cells. Mice were followed twice per week for development of leg tumor.

Identification of a heteroclitic peptide of RNEU₄₂₀₋₄₂₉ that can immunize mice in vivo against outgrowth by the mammary tumor

Identification of the immunodominant neu peptide allowed us to search for altered peptide analogs with potentially enhanced immunogenicity. Altered forms of RNEU₄₂₀₋₄₂₉ were created by substituting alanine at each of the 10 positions. This type of approach has been successful in identifying heteroclitic T cell peptides in both rodent and human settings (6, 49–54). In the majority of cases, substitutions did not enhance recognition. However, when alanine was substituted for glutamate at position 2, this peptide (designated RNEU₄₂₀₋₄₂₉A2) demonstrated markedly improved recognition by the T cell clone FVB/N V β 4A in a lysis assay as compared with wild-type peptide (Fig. 3). Interestingly, the heteroclitic peptide was found to have a lower binding affinity than the wild-type RNEU₄₂₀₋₄₂₉ peptide in a T2D^q MHC stabilization assay (data not shown), suggesting that its improved stimulatory capacity was instead due to the enhanced stability of the TCR/MHC/peptide complex.

To determine whether this heteroclitic peptide can immunize mice against mammary tumor expressing the natural RNEU₄₂₀₋₄₂₉ epitope, both wild-type RNEU₄₂₀₋₄₂₉ and the heteroclitic variant RNEU₄₂₀₋₄₂₉A2 were used to vaccinate mice. Dendritic cells derived from FVB/N mice were pulsed in vitro with either of these peptides (or with an irrelevant peptide) and then injected s.c. into FVB/N and neu-N mice followed by a s.c. NT2 tumor challenge. As shown in Fig. 5, mice immunized with dendritic cells pulsed with the wild-type peptide developed tumor at about the same rate as mice immunized with an irrelevant peptide ($p < 0.15$ for FVB/N mice; $p < 0.39$ for neu-N mice). However, FVB/N mice immunized with the heteroclitic peptide showed a lag in tumor growth as compared with FVB/N mice immunized with the irrelevant peptide ($p < 0.012$). Although not statistically significant, neu-N mice demonstrated a promising trend toward protection when vaccinated with the heteroclitic peptide ($p < 0.21$).

Discussion

We have identified a MHC-I epitope in rat HER-2/neu, RNEU₄₂₀₋₄₂₉, which is the dominant target of the CD8⁺ T cell response in FVB/N mice. This peptide, which is contained in the extracellular region of neu, is recognized by all neu-specific CD8⁺ T cell lines and clones derived from vaccinated FVB/N mice regardless of the neu-targeted vaccine approach used for immunization. This was true even though vaccination induced an oligoclonal neu-specific T cell response as determined by the panel of

T cell lines and clones tested expressing several different TCR V β types. This was unexpected because the neu gene is 4kB in size and encodes for a large protein. However, other studies have reported similar findings demonstrating that a single viral or tumor antigenic epitope is recognized by a panel of T cells derived from immunized mice (8, 55–57). In contrast, neu-specific T cells isolated from patients with neu-expressing breast and ovarian cancer typically recognize multiple epitopes in both the extracellular and intracellular domains of the protein (58–63). Therefore, our data suggest that the FVB/N nontolerized mice recognize neu as a foreign Ag.

FVB/N mice were protected against inoculation with a neu-expressing in vitro tumor line (derived from naturally arising mammary tumors in neu-N mice) when T cells specific for this epitope were adoptively transferred. This indicates that RNEU₄₂₀₋₄₂₉ is the immunodominant MHC-I epitope in rat neu that serves as the naturally expressed tumor rejection target on spontaneously arising neu-expressing tumors. It is interesting to note that RNEU₄₂₀₋₄₂₉ differs from the corresponding murine amino acid sequence by 3 aa (64). Furthermore, RNEU₄₂₀₋₄₂₉ specific T cells do not recognize the murine peptide in a ⁵¹Cr release lysis assay (data not shown). This probably explains its high degree of immunogenicity in the FVB/N mice.

Vaccination with the RNEU₄₂₀₋₄₂₉ peptide pulsed onto dendritic cells did not demonstrate antitumor immunity. This is not surprising, because vaccinating mice or patients with solely MHC-I tumor epitopes has produced only modest results in most studies. For some Ags, altering the wild-type MHC-I epitope so that it binds more strongly to MHC and/or demonstrates greater recognition in vitro by Ag-specific T cells improves the immunization potential and the clinical outcome (54, 65–67). In this study, we show that vaccinating FVB/N mice with dendritic cells pulsed with a heteroclitic variant of the wild-type epitope also induces improved protection against tumors that express the natural RNEU₄₂₀₋₄₂₉ epitope as compared with immunization with the RNEU₄₂₀₋₄₂₉ epitope itself. neu-N mice show a promising trend toward protection when vaccinated with the heteroclitic peptide but not to the degree seen in FVB/N mice. This may reflect the neu-specific tolerance seen in neu-N mice. In any case, this regimen proved to be far less efficacious for either strain of mice than our whole-cell vaccine, further supporting the concept that vaccines that induce both CTL and Th cell responses may be more effective than vaccines that only enhance the CTL response (41, 48).

Few studies have been published dissecting the immune responses in *neu-N* mice, which are transgenic for rat *neu* and therefore express a tissue-specific tumor Ag (24, 26–29, 44). We have previously shown that these mice are tolerant to their transgene as compared with the FVB/N strain from which they were derived and that this tolerance is found both in the humoral and T cell arms of the immune response (24). However, we do not yet know the mechanism of this tolerance. It appears from our studies that *neu-N* mice given a whole-cell 3T3neuGM vaccine do not develop T cells specific for the immunodominant peptide in *neu*, although mice vaccinated with the heteroclitic version of the peptide show a degree of protection from *neu*-expressing tumor challenge. This may indicate that, although the predominant response to *neu* in *neu-N* mice is to other, less immunogenic epitopes, T cells specific for the immunodominant peptide may be induced. However, *neu-N* mouse-derived T cells may recognize the immunodominant epitope with a lower avidity as compared with FVB/N-derived T cells. This tolerance may occur in the thymus, in the periphery, or in both compartments. The identification of RNEU_{420–429} as the immunodominant epitope contained in the rat *neu* protein will facilitate the further characterization of vaccine-induced immune responses in the rat *neu*-transgenic mouse model. To that end, an MHC/peptide tetramer can be made to identify T cells specific for the immunodominant epitope, because it is known that the restricting MHC molecule is H-2D^a. Identification of other epitopes in rat *neu* is also ongoing.

Acknowledgments

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